LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

LLNL-JRNL-431151

# NIF Target Assembly Metrology Methodology and Results

E. T. Alger, J. J. Kroll, R. C. Montesanti, J. D. Hughes, M. F. Swisher, J. S. Taylor, K. S. Segraves, D. M. Lord, C. Castro, G. J. Edwards

May 11, 2010

Fusion Science and Technology

**Disclaimer**

**NIF Target Assembly Metrology Methodology and Results**

E.T. Alger,[1] J. Kroll,[2] E.G. Dzenitis,[2] R. Montesanti,[2] J. Hughes,[2] M. Swisher,[3] J. Taylor,[2] K. Segraves,[3] D.M. Lord,[2] J. Reynolds, [2] C. Castro, [2] and G. Edwards[2]

[1]General Atomics

P.O. Box 85608, San Diego, California 92186-5608

[2]Lawrence Livermore National Laboratory

P.O. Box 808, Livermore, California 94550

[3]IAP

7000 East Avenue, Bldg. 415, Livermore, California 94550

## Abstract

Inertial confinement fusion (ICF) experiments at the National Ignition Facility (NIF) require cryogenic targets at the 1 cm. scale to be fabricated, assembled, and metrologized to micron level tolerances. During assembly of these ICF targets there are physical dimension metrology steps to be made of the components, sub-assemblies, and completed targets. Metrology is primarily completed using optical coordinate measurement machines that provide repeatable measurements with micron-precision, while also allowing in-process data collection for absolute accuracy in assembly. To date, fifty-one targets have been assembled and metrologized and thirty-four targets have been successfully fielded on NIF relying on this metrology data. In the near future, ignition experiments on NIF will require tighter tolerances and more demanding target assembly and metrology capability.

Metrology methods, calculations, and uncertainty estimates will be discussed. Measurements from recently fielded targets on NIF will be reviewed as an assessment of assembly process performance and future assembly and metrology improvement efforts will be highlighted.

**Target assembly description**

A NIF cryogenic target is comprised of a number of components that form two main subsystems, the base and the target. The base provides the target interface to external gas handling and electrical systems as well as to the cryogenic cold head, see figure 1. The target is composed of two distinct subsystems, the thermo-mechanical package and physics package.[4] The thermo-mechanical package (TMP) consists of TMP shells, diagnostic band, various windows and cooling arms. This package has an engineering purpose such that it allows for precision repeatable assembly, while accommodating changing attributes of target components and maintaining thermal symmetry of the target[17]. See figure 2.

The physics package consists of the hohlraum, laser entrance hole (LEH) inserts, tents, and the capsule fill tube assembly (CFTA). The physics package meets the specifications set forth by the physics experimental requirements. The TMP and physics components and subassemblies are assembled into a completed target at the "final assembly" step in the production process.[12] This step includes threading the CFTA into the diagnostic band, capturing the capsule in the tents of the TMP/hohlraum subassemblies, and attaching the target to the base.[2]

Assembly tolerances are derived from physics flow down requirements, fabrication tolerances, and metrology capabilities. The table in figure 3 lists the primary final assembly requirements and tolerances.

Following final assembly, over 400 dimensional measurements are made and over 70 values are reported per target. During the Energetics Campaign in 2009, 31 cryogenic targets were shot of 54 targets that were assembled and metrologized. These measurements, in addition to others made during the production process, resulted in over 12,500 reported values.

**System Requirements**

The metrology system used for these measurements had four main requirements. First, the system had to be able to make all of the pertinent measurements via non-contact methods due to the fragility of the targets. Second, the system had to work over the entire volume of a target mounted to a base and embedded in the assembly hardware. This volume is approximately the size of a shoebox. Third, assembly tolerances are typically in the 5-20 μm range and therefore the goal for the measurement system was to be 10 times better or in the 1-2 μm accuracy and repeatability range. Finally, it was also critical to have the ability to metrologize targets being produced at a rate of 1-2 targets per day.

**Metrology System**

The metrology tool used for dimensional measurements of NIF cryogenic targets was the Quest series optical coordinate measuring machine (OCMM) by Optical Gaging Products (OGP®). The OGP® OCMM met the measurement system requirements including measurement volume, various non-contact measurement methods, accuracy and repeatability, and production rate requirements. The coordinate system of the OCMM is shown in figure 4. The OCMM has a datasheet accuracy value in x and y, of 1.5 μm. The z-accuracy is 1.5 μm to 10 μm depending on the hardware configuration of the OCMM. Longer working distances allow room for assembly hardware during the assembly or metrology processes. The measurement accuracies also have a length dependent factor which is typically not an issue at the scale of a target.

Generally, the shorter the working distance of the system, the better the measurement accuracy. During metrology there is no extraneous hardware and therefore a sensor that has a shorter working distance but improved accuracy can be used. The working volume, of the OCMM models in the production facility, is large enough for assembling a target with a base with all of the necessary assembly hardware in place.

The machine software, MeasureMind® 3D, allows the user to record measurement routines and automate the measurement process. Automating the process removes as much operator error as possible. The x/y-measurements are made via video images. The z-dimension measurements can be completed in order of least to most accurate by optical focus, a Through-the–Lens (TTL) laser, or a Rainbow Probe. The optical focus relies on software to determine the best focus point via contrast. Experience has shown a real world repeatability of about 5-20 µm dependent on the material and surface characteristics of the part being inspected. The TTL is an interferometric laser and its accuracy is dependent on the lens configuration. Using different lens combinations, accuracy can range from 2-5 µm in addition to the stage accuracy of approximately 1.5 µm and the working distance is 19 mm to 200 mm. The Rainbow Probe uses a white light source and spectral analysis of the reflected light to produce accuracy at the nanometer scale providing the pertinent feature is within its measuring range. However, if the measurement requires movement in the z direction the accuracy of the system is approximately 1.5 µm due to the stage accuracy. The Rainbow Probe installed in the target production machines has a working distance of 5.7 mm.

## Measurement Results

Dimensional metrology will be shown for key measurements taken during the metrology step following final assembly of the 2009 Energetics Campaign targets. The data will be presented via moving range process control charts.[7] Control charts were used as a tool to monitor the assembly processes during production with the intent of discovering trends early and making process adjustments before any non-conformance issues occurred. These graphs are normalized on the y-axis to show percent of tolerance. The x-axis shows the target number in chronological order of the assembly date. Each plot shows the metrology data, data average, upper/lower specification limits and upper/lower control limits. The control limits are equal to the data mean plus or minus 3 times the moving range average and are used as indicators as to whether a process is in control. A process is considered in control if the data points are randomly distributed and within the control limits. Error or uncertainty estimates are made by calculating the root sum square of the datasheet accuracy values where available and relying on experience where there is a void of information. These uncertainties are estimated to be 2-sigma values.

There are hundreds of measurements made during the final stages of target assembly and not all of the data will be discussed in this paper. Therefore, only the most important items are detailed in the following paragraphs. The methodology, estimated uncertainties, and results will be discussed for the diagnostic port angular alignment, target location with respect to the target base, and capsule position with respect to target center.

**Diagnostic Port Angular Alignment With Respect to the Base**

The diagnostic port angular alignment with respect to the target base was measured on each target. The angular alignment specification was a nominal value dependent on the primary experimental diagnostic location +/- 0.250 degrees. This alignment was imperative so that the diagnostic, the gated xray diagnostic (GXD), could align to the target and record experimental results.

During assembly, the assembler positions the hohlraum relative to the TMP shell at the Hohlraum Insertion Station (HIS). This assembly step is performed by visually aligning features on the hohlraum and TMP shell.[9] The measurement is then completed on the OCMM after the hohlraum is inserted into the TMP shell and glued in place. Metrology data from the subassemblies detailing the location of the hohlraum with respect to the TMP shell, in conjunction with final metrology data detailing the position of the TMP shell with respect to the base, are used to determine the diagnostic port location as shown in figure 5. The same information is used to determine how well the top and bottom target halves are positioned with respect to one another. The angular alignment is the sum of the angular alignments at the subassembly and final metrology measurement steps.

Process improvements were made during the production run and the results can be seen in figure 6. During the early stages of the production run it was evident that the assembly process was not in control and approached or exceeded specification limits. Two changes were made at the HIS that allowed the operator greater access to the component alignment features. The resolution and magnification of the station microscope was upgraded and portions of the assembly station were modified to allow the operator a more detailed view of the process. Following the upgrades the process variability improved and the control limits tightened. However, there was still a bias error between the assembly and metrology stations. This error was due differences in the automatic measurement routines. A standardized routine was deployed, which corrected the difference toward the later stage of the production run. The remaining outliers shown in the plot were due to off-normal events such as parts with predicted interference fits. Based on the OCMM x/y-measurement uncertainty, the estimated measurement uncertainty was 0.04 degrees.

**Target Location With Respect to the Base**

The target location with respect to the base was required to be within nominal position in x, y, z to within +/- 0.500 mm. Roll, rotation about the y axis, of the target had to be within +/- 1.0 degrees and pitch, rotation about the x axis, within +/- 0.250 degrees of the nominal values. See figure 7 for an explanation of the target coordinates. These requirements are necessary so that systems including the target positioner, alignment systems, and diagnostics can function properly. The target location in x/y is the measured distance between the center of the upper LEH insert and the datum features on the target base. Figures 8 and 9 detail the target position in x and y coordinates relative to the base. In both figures the processes before target #13 were much more variable. During this time proper measurement methods for assembly and metrology were developed. A change was then made to standardize the measurement methods between the assembly and metrology machines. After the measurement methods were standardized, the target x and y positions improved and were consistently within specification limits. The estimated uncertainty was less than 0.02 mm. This uncertainty is based on small sample statistics from a measurement repeatability study performed during the Energetics Campaign. The main source of the error is optically detecting the edges of the based datum features. These features have since been redesigned to address this issue.

The z-position was measured via the TTL laser with a 0.45 or 0.50 magnification lens as the distance from the top of the TMP shell and the target base datum features perpendicular to the xy-plane of the target. The target position in z is shown in figure 10. A change was made by target #5 during the base assembly step to improve the base metrology process and verify that the bases were within specification prior to final target assembly. Prior to this change the bases were assumed to be within specification due to their component fabrication tolerances. The improved metrology method was to use the OCMM rather than use an existing less accurate mechanical indicator set-up. Also note that even after the improved metrology during base assembly the targets were on average biased in the negative direction. Although not shown, a similar trend was exhibited during base assembly such that the extension, where the target is attached to the base, was consistently lower in z relative to the base. The estimated uncertainty was 0.034 mm based on repeatability study statistics.

Rotation of the target relative to the base was measured by fitting planes to z-measurement data on the TMP shell and base datum features. The rotation about x as shown in figure 11 shows a similar trend to the target location in z. The same metrology improvement at the base assembly step positively affected the pitch of the target relative to the base at target #5 and thereafter.

The rotation about the y-axis, or roll of the target, has a relatively large tolerance of +/- 1 degree. This is because the target positioner can adjust in this direction more than the others. The assembly and measurement processes did not change for this parameter, see figure 12. Note that the parameter was within specifications most of the time but consistently biased in the negative direction. This was due to the assembly procedure and fixture that does not correct for a torque that is applied when attaching the long extension arm of the base to its mounting hardware. Based on repeatability study statistics the estimated uncertainty for both the pitch and roll was better than 0.02 degrees.

**Capsule Position With Respect to Target Center**

During the Energetics Campaign, the capsule had to be positioned in the target center within +/- 20 μm axially and +/- 25 μm radially. Radial measurements are made via concentricity measurements of the capsule outer diameter relative to the LEH insert inner diameter. The axial capsule position was calculated using multiple measurements including: target axial length, LEH insertion depths, LEH insert thickness, capsule radius, and the measured distance from the top of the capsule to the top of the TMP shell.

Figures 13 and 14 show the capsule radial positions in the x and y directions. The y-direction is nearly in-line with the base extension and fill tube. Both of these processes appear in control and within specification limits. However, the average data point / trend in the y-direction is biased in the negative direction at approximately 20% of the tolerance limit or 5um. This observation via data also correlates with what was observed during assembly. Capsules frequently make small moves near the end of the assembly process. There are a few hypotheses regarding the causes for the movement but more investigation is required to determine the cause conclusively.

Late in the production run the process was changed such that the capsule was not centered but rather biased or positioned off-center during assembly. The capsule was positioned approximately 5 µm in the positive y-direction to see if there was an effect on the capsule position post-assembly. The biasing during assembly had the predicted effect such that for a small sample of targets the capsule radial position average improved. Future engineering effort will focus on this phenomenon with the intent of determining the root cause of the problem rather than compensating for its affect.

Figure 15 shows the capsule axial position with respect to the center of the hohlraum. The calculation is based on the target length, LEH insert thickness and insertion depth and capsule position with respect to the TMP shell. This data is shown within the control limits and specification limits. During the Energetics Campaign the axial position requirement was within +/- 20 µm of target center. In the future ignition tuning target capsule position tolerances will be tightened up to 50 % of former values or within +/- 10 µm axially. This means that given the current assembly process, the production yield will decrease and measurement precision to tolerance ratios will increase.

To compensate for these issues the assembly machine was upgraded to include the TTL laser probe.[5,6,8] This probe will allow the final assembly machines to make measurements to within 5 µm rather than relying on optical contrast focus for measurements when positioning the capsule axially. The metrology machine will also change processes so that all pertinent axial measurements will be completed using the Rainbow Probe which will increase the z-axis measurement accuracy to nearly 1.5 µm rather than 2-5 µm achieved using the TTL. The Energetics Campaign capsule axial position estimated uncertainty based on data sheet values was 0.006 mm.

**Conclusions**

There were many lessons learned during the dimensional metrology of cryogenic targets for the NIF Energetics Campaign and the list below is not all inclusive. This was the first use of metrology tools developed during pilot production runs and for D-T ice layering experiments.

Using control charts as real-time production tools yields actionable information that can both increase production yield and throughput. The information can also be used to focus process improvement resources. Tracking of measurement values and other production related items was a work-in-progress during this first campaign. Looking forward, the systems are now in place to monitor each process and base decisions on real time information. This same information can be used for predicting yield based on future specification changes.

Automation of the metrology routines resulted in a more than 10 times metrology throughput improvement as well as increased measurement repeatability. Initially, these timeconsuming measurements were performed manually for each target. With time, standard measurement routines were developed that both decreased measurement time and standardized the measurements so that the process was not as dependent on the operator.

The OCMM has proven to be a reliable, accurate, and necessary system to make measurements of complex targets for NIF. OGP® OCMMs are now in use for multiple assembly machines as well target metrology, and resulting measurement data has been collected for each NIF cryogenic target to date.

Early predictions of measurement uncertainties based on datasheet values were validated through post campaign analysis of small data samples. Many targets were measured multiple times using the programmed routines. In most cases the repeatability information gained from these measurements yielded uncertainties that were smaller and the same order of magnitude as the estimates derived from datasheet accuracy values.

**Future Challenges**

Target axial measurements are difficult given the measurement precision required, the specification tolerances, and the number of measurements in the calculation. For these reasons continued effort will focus on improved assembly and measurement capabilities along this axis. The TTL upgrade to the assembly OCMM will help meet future capsule axial positioning requirements by improving in-process measurement accuracy to approximately 5µm. The metrology OCMM will use the Rainbow Probe for z-axis measurements improving the measurement accuracy to 1.5µm.

Capsule radial positioning improvements will be made by better positioning the capsule during assembly. Effort will focus on determining an engineering rationale for capsule position bias during assembly. Once the mechanism is understood, the correct remedy will be chosen to fix rather than compensate for the capsule movement during assembly.

The fixtures used for metrology were developed prior to the Energetics Campaign. A dedicated set of upgraded tooling will be developed based on the experience from this campaign. The dedicated tooling will have the primary goal of increasing repeatability and throughput of the metrology station.

New targets designs are being developed. These new designs will require new assembly and metrology steps, methods, and capabilities. The entire metrology process will be an on-going process improvement and research and development effort moving forward.

**Acknowledgements**

In accomplishing this work we also acknowledge contributions by John Hammond of Indicate Technologies and Bill Verwys and Kevin Christensen of Quality Vision International.

This work was performed under the auspices of the U.S. Department of Energy by General Atomics under Contract DE-AC52-06NA27279 and by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

**References**

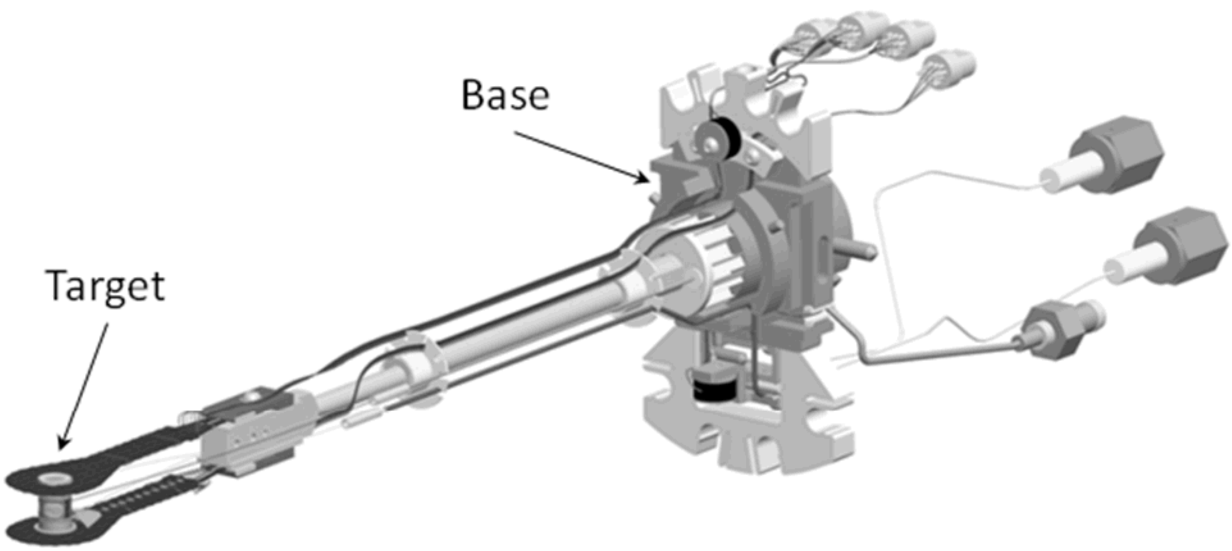
1. S. W. HAAN et al., "Rev 3 Update for Requirements for NIF Ignition Targets", *Fusion Science and Technology*, **55**, 227 (2009)
2. E. T. ALGER et al., "Experimental D-T Ice-Layering Target Assembly", *Fusion Science and Technology*, **55**, 269 (2009)
3. E. T. ALGER et al., "NIF Target Assembly Metrology Methodology and Results", presented at 19th Target Fabrication Specialists Mtg., Orlando, FL, February 21-26, 2010.

4. J. KROLL et al., "Design of a Cryogenic Target for Indirect Drive Ignition Experiments on NIF " , presented at 19th Target Fabrication Specialists Mtg., Orlando, FL, February 21-26, 2010.
5. R. C. MONTESANTI et al., "Robotic System for Precision Assembly of NIF Ignition Targets ", *Proceedings of the American Society for Precision Engineering 2008 Annual Meeting*, (2009)
6. R. C. MONTESANTI et al., "Lessons from Building Fusion ignition Targets with the Precision Robotic Assembly Machine", presented at 19th Target Fabrication Specialists Mtg., Orlando, FL, February 21-26, 2010.
7. *Six Sigma Statistics with Excel and Minitab*, 1st ed., ISSA BASS, McGraw Hill, New York (2007)
8. C. CASTRO et al., "Building Fusion Targets with a Precision Reconfigurable Assembly Station", presented at 19th Target Fabrication Specialists Mtg., Orlando, FL, February 21-26, 2010.
9. K. SEGRAVES et al., "Building Fusion Targets with a Precision Reconfigurable Assembly Station", presented at 19th Target Fabrication Specialists Mtg., Orlando, FL, February 21-26, 2010.
10. J. FLORIO et al., "Unconverted Light Shields for Use on the NIF", presented at 19th Target Fabrication Specialists Mtg., Orlando, FL, February 21-26, 2010.
11. D. LORD et al., "Proven Bonding Methods for Complex Cryogenic Target Geometries used in the National Ignition Campaign", presented at 19th Target Fabrication Specialists Mtg., Orlando, FL, February 21-26, 2010.

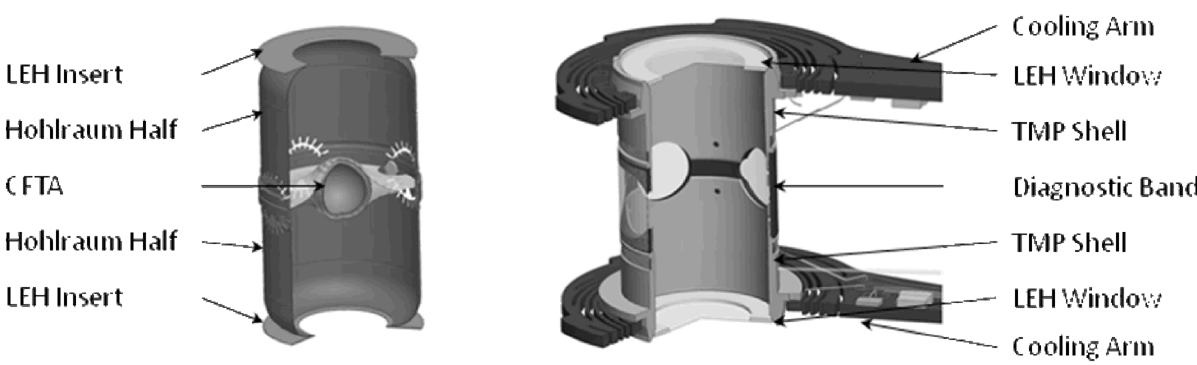
12. E. DZENITIS et al., “Target Production for the First NIF Cryogenic Experiments”, presented at 19th Target Fabrication Specialists Mtg., Orlando, FL, February 21-26, 2010.
13. M. SWISHER et al., “Advances in Building Fusion Ignition Targets with the Precision Robotic Assembly Machine”, presented at 19th Target Fabrication Specialists Mtg., Orlando, FL, February 21-26, 2010.
14. OGP® website; available on the internet at http://www.OGPnet.com (2010)
15. Indicate Technologies; available on the internet at http://www.indicate1.com
16. National Ignition Facility and Photon Science Web site; available on the internet at https://lasers.llnl.gov
17. J. S. TAYLOR et al., “Deterministic Fabrication of NIC Targets”, presented at 19th Target Fabrication Specialists Mtg., Orlando, FL, February 21-26, 2010.

**Figures**

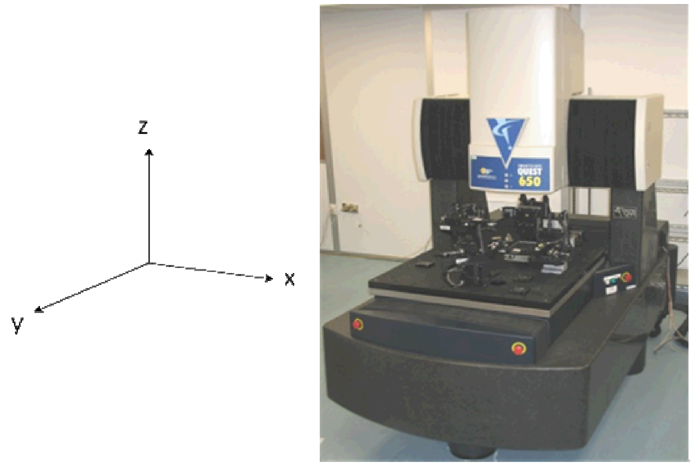
a. Figure 1: Energetics Campaign NIF Cryogenic Target Attached to Base Model




b. Figure 2: Target Physics and Engineering Packages



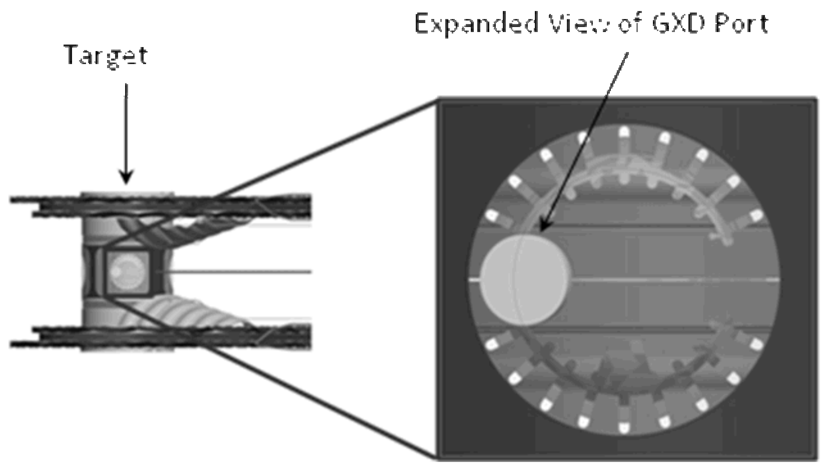

c. Figure 3: OGP® OCMM With System Coordinate System



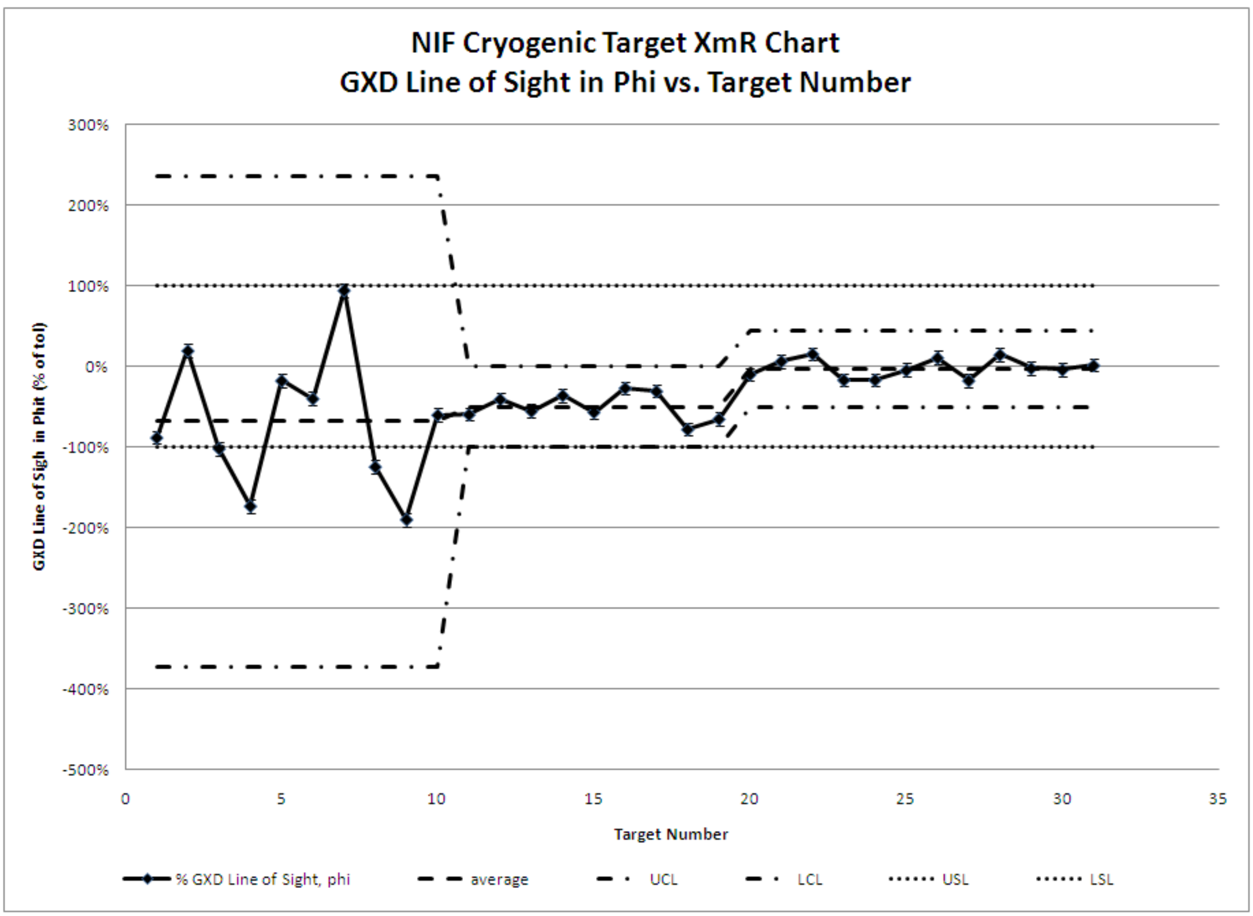

d. Figure 4: Target Assembly Dimensional Requirements Table

| Category | Description | Specifications |
|---|---|---|
| **TMP Subassembly** | Hohlraum to TMP Can Clocking (deg) | 7 +/- 1 degree |
| | LEH Insertion Depth (mm) | 0.350 +/- 0.011 mm |
| | Hohlraum Insertion Depth (mm) | 1.770 +/- 0.006 mm |
| **Capsule Position** | Capsule Axial Position from Nominal wrt Target Center in Z (um) | 0 +/- 10 um |
| | Capsule Radial Position wrt LEH (um) | 0 +/- 12 um |
| **Diagnostic Line of Sight** | GXD Line of Sight, phi (deg) | 315 +/- 0.5 degree |
| | GXD Line of Sight, theta (deg) | 90 +/- 0.5 degree |
| | Hohlraum GXD Notch Upper to Lower Angular Alignment (deg) | 90 +/- 0.25 degree |
| **Hohlraum Gaps and Length** | Gap (z) between hohlraum halves (um) | 20 +/- 8um |
| | Gap between hohlraum and LEH, upper/lower (um) | 23 +/- 6um |
| | Nominal Hohlraum Inner Length, total (um) | 10052 +/- 20um |
| **Target Location wrt Base** | Target Pitch Offset, Rx, relative to Base Datum (deg) | 0 +/- .250 degrees |
| | Target Roll Offset, Ry, relative to Base Datum (deg) | 0 +/- 1 degrees |
| | Target Center Offset, X/Y, relative to Base Datum (mm) | 0 +/- .500 mm |
| | Target Center Offset, Z, relative to Base Datum (mm) | 0 +/- .500 mm |
| **Fiducial Surface** | Upper/Lower Fiducial Surface to LEH Midplane (mm) | 5.426 +/- .010 mm |
| **Fiducial Surface to LEH Concentricity** | Upper/Lower Fiducial Surface ID Location wrt LEH axis, x/y (mm) | 0 +/- .005 mm |
| **Shield Location** | Shield Location at x and y (mm) | 0 +/- 0.250 mm |

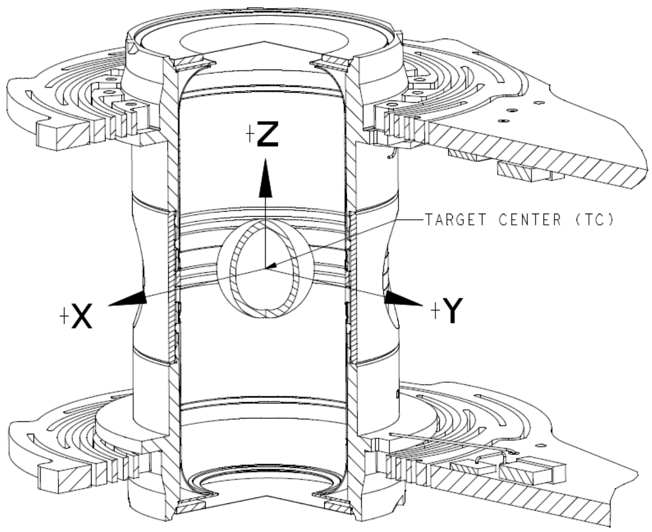
e. Figure 5: GXD Port Angular Location Model



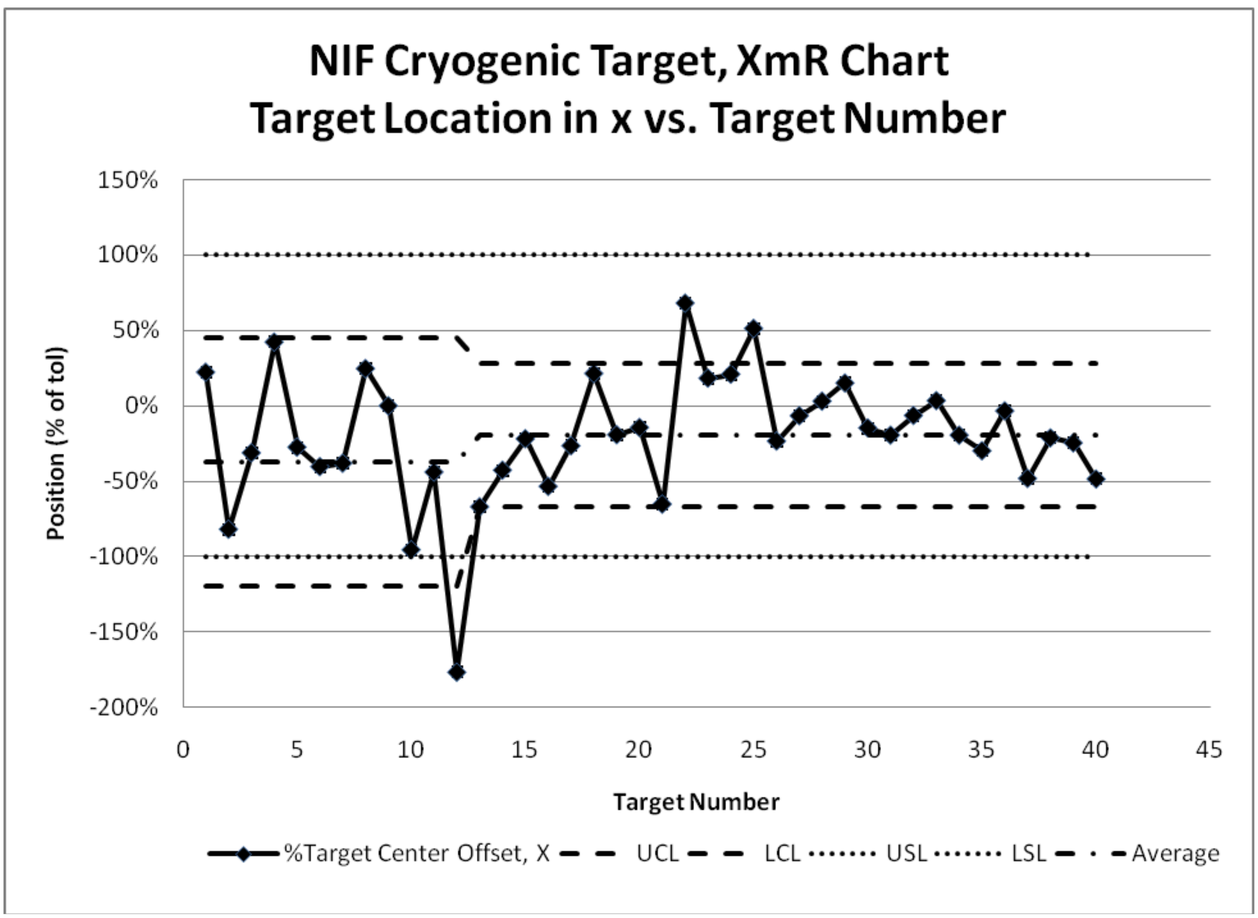

f. Figure 6: GXD Port Angular Alignment vs. Target Number Graph



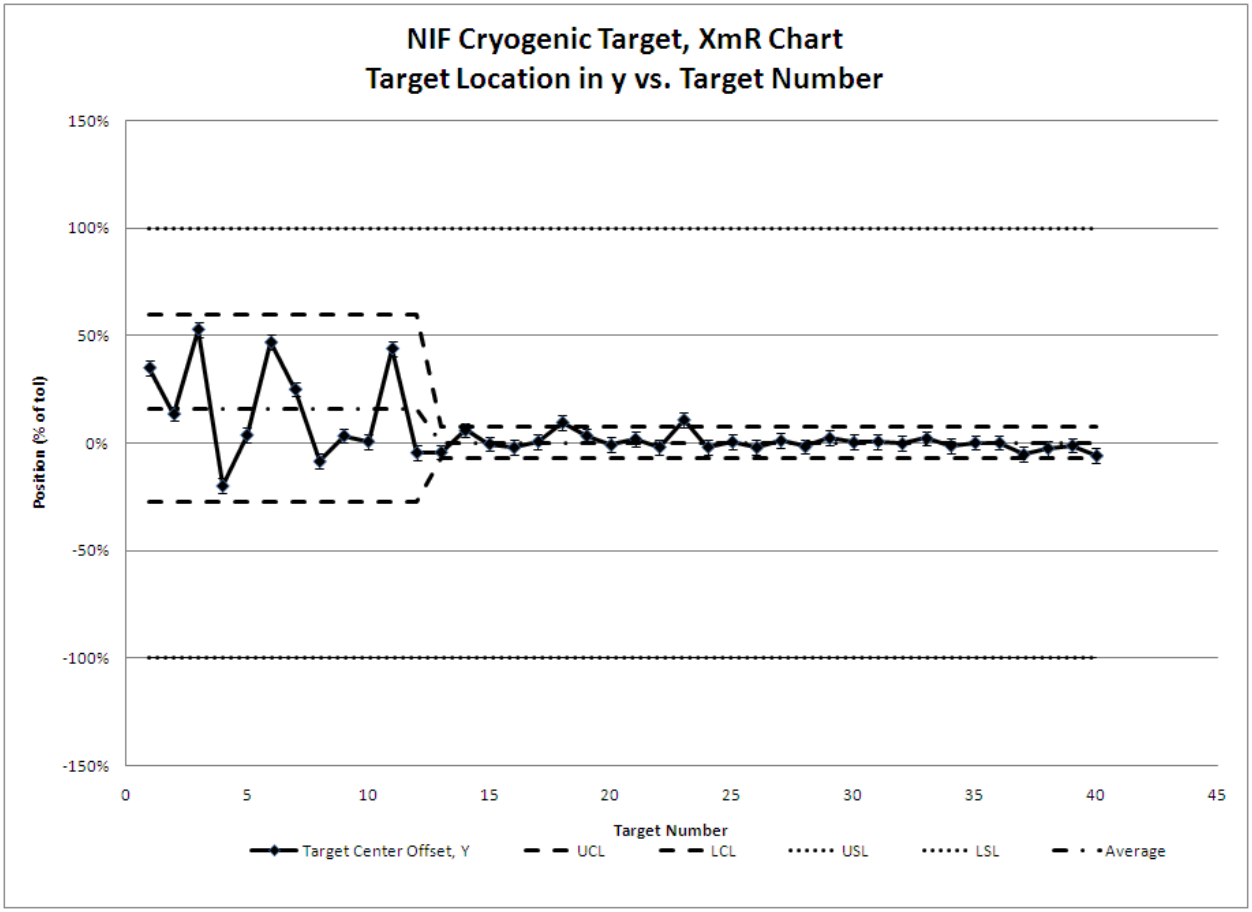
g. Figure 7: Target Coordinate System



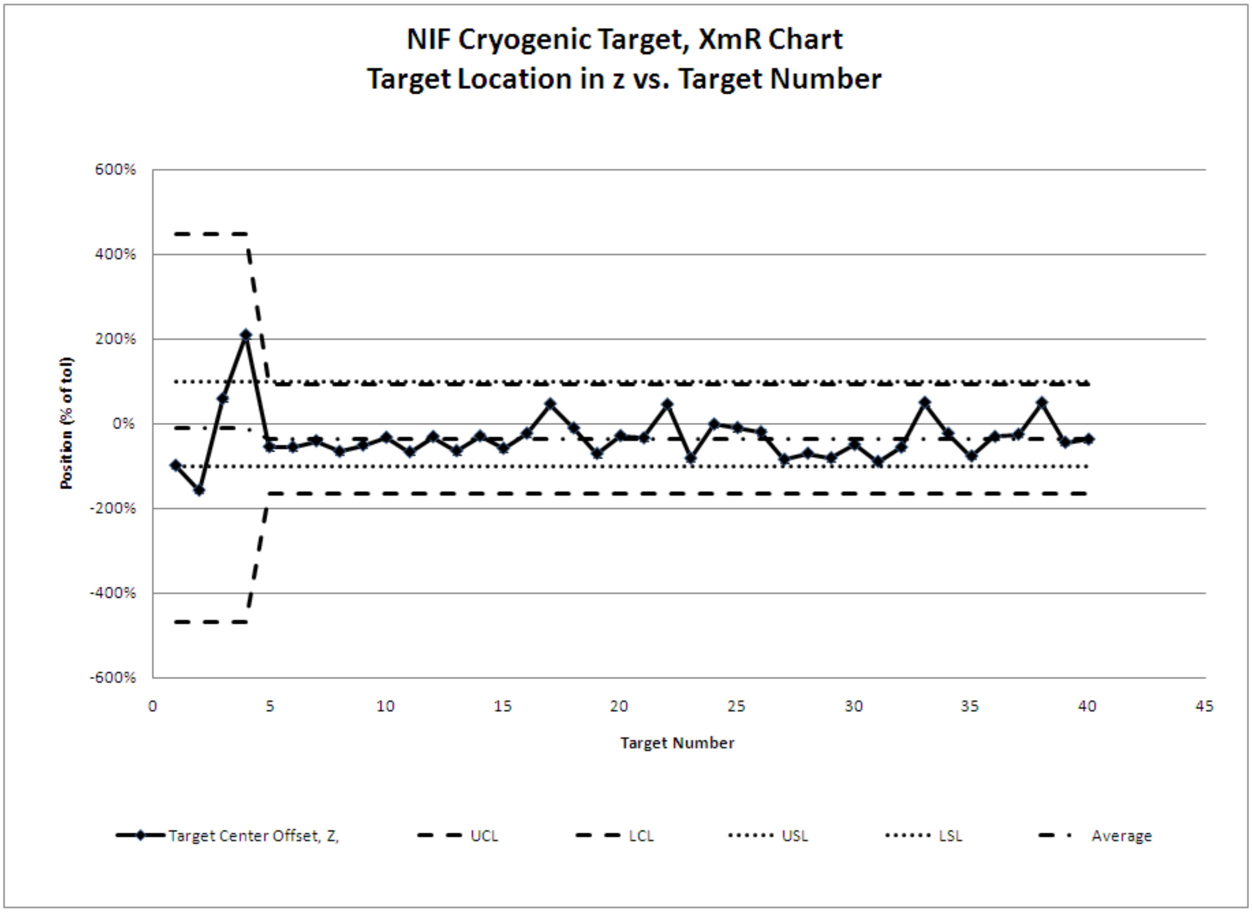

h. Figure 8: Target Location Relative to Base in X Direction Graph



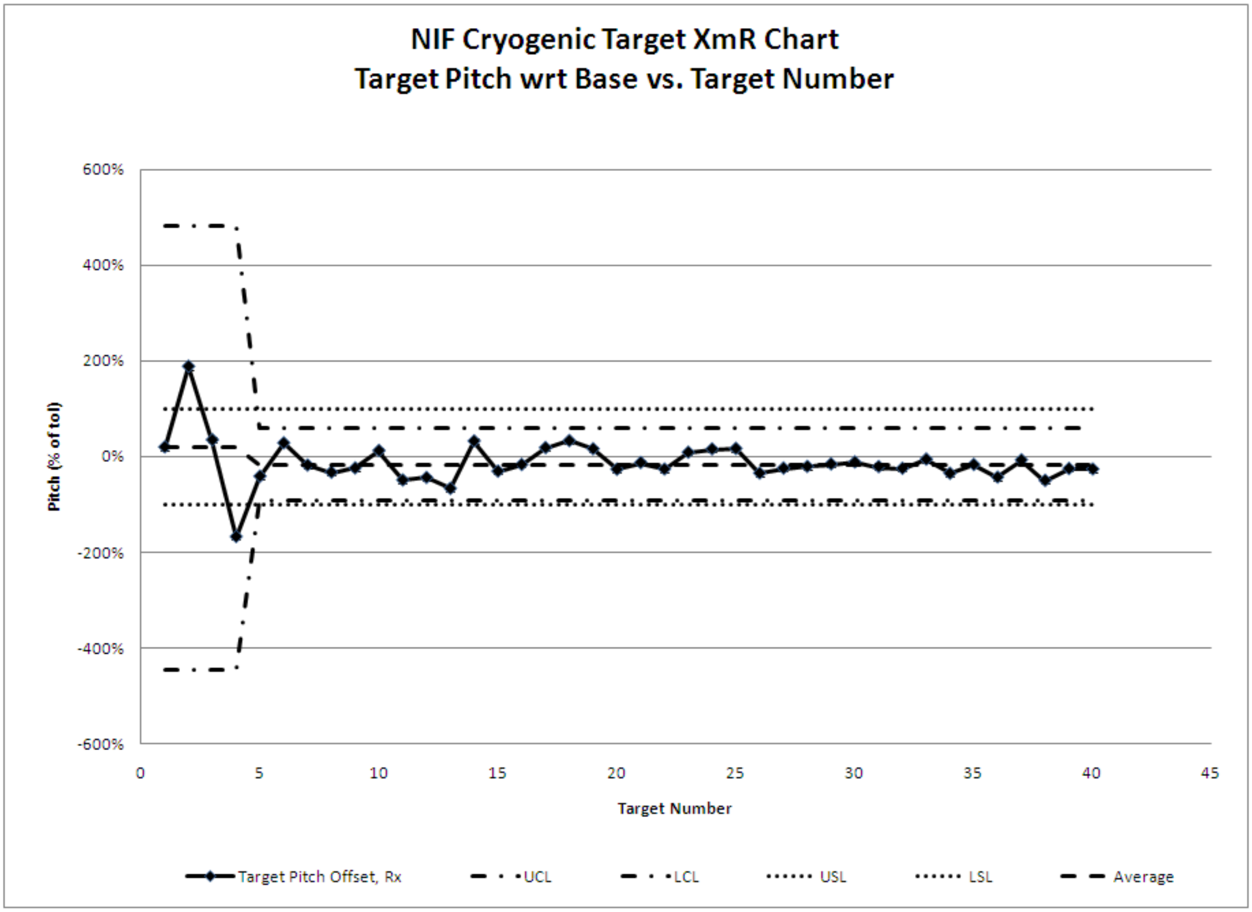
i. Figure 9: Target Location Relative to Base in Y Direction Graph



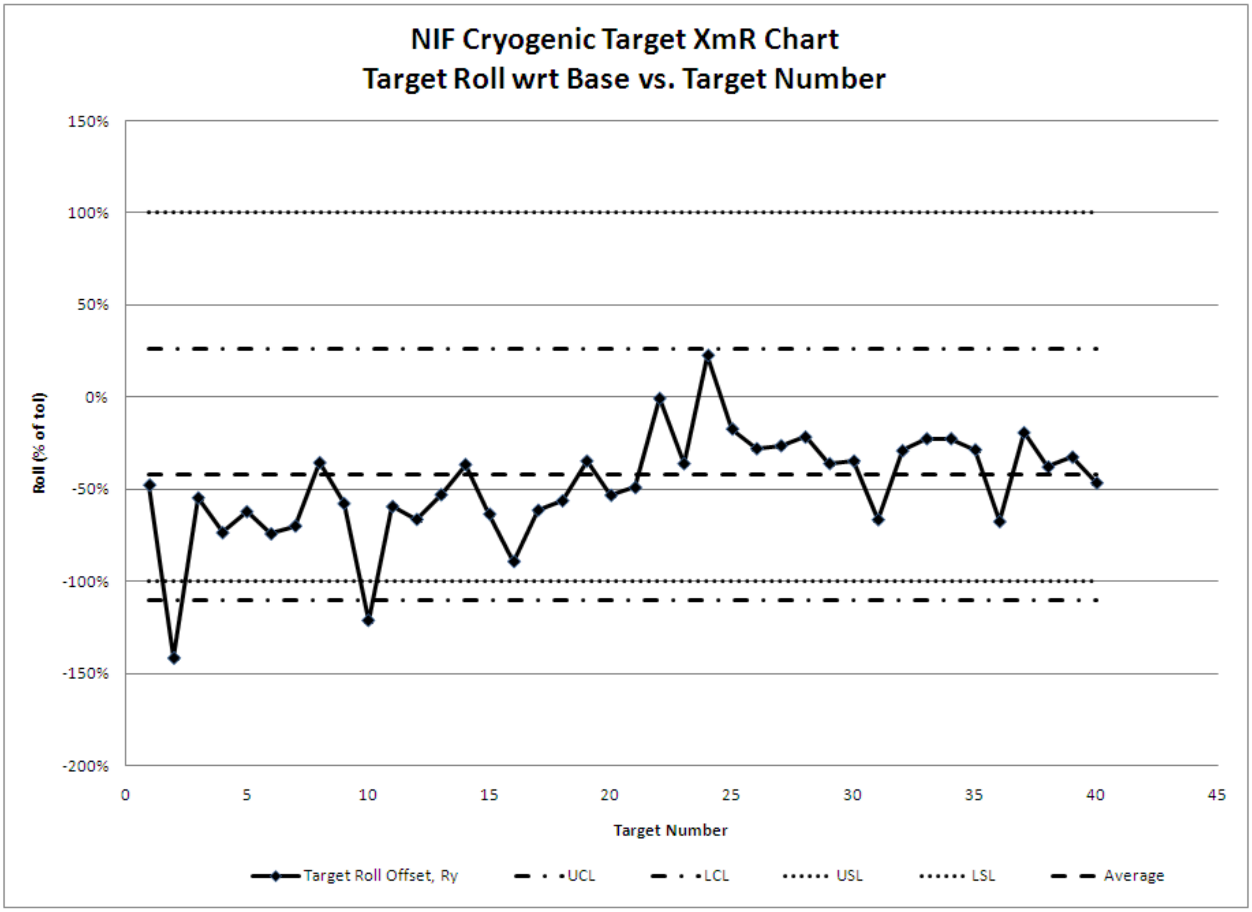

j. Figure 10: Target Location Relative to Base in Z Direction Graph



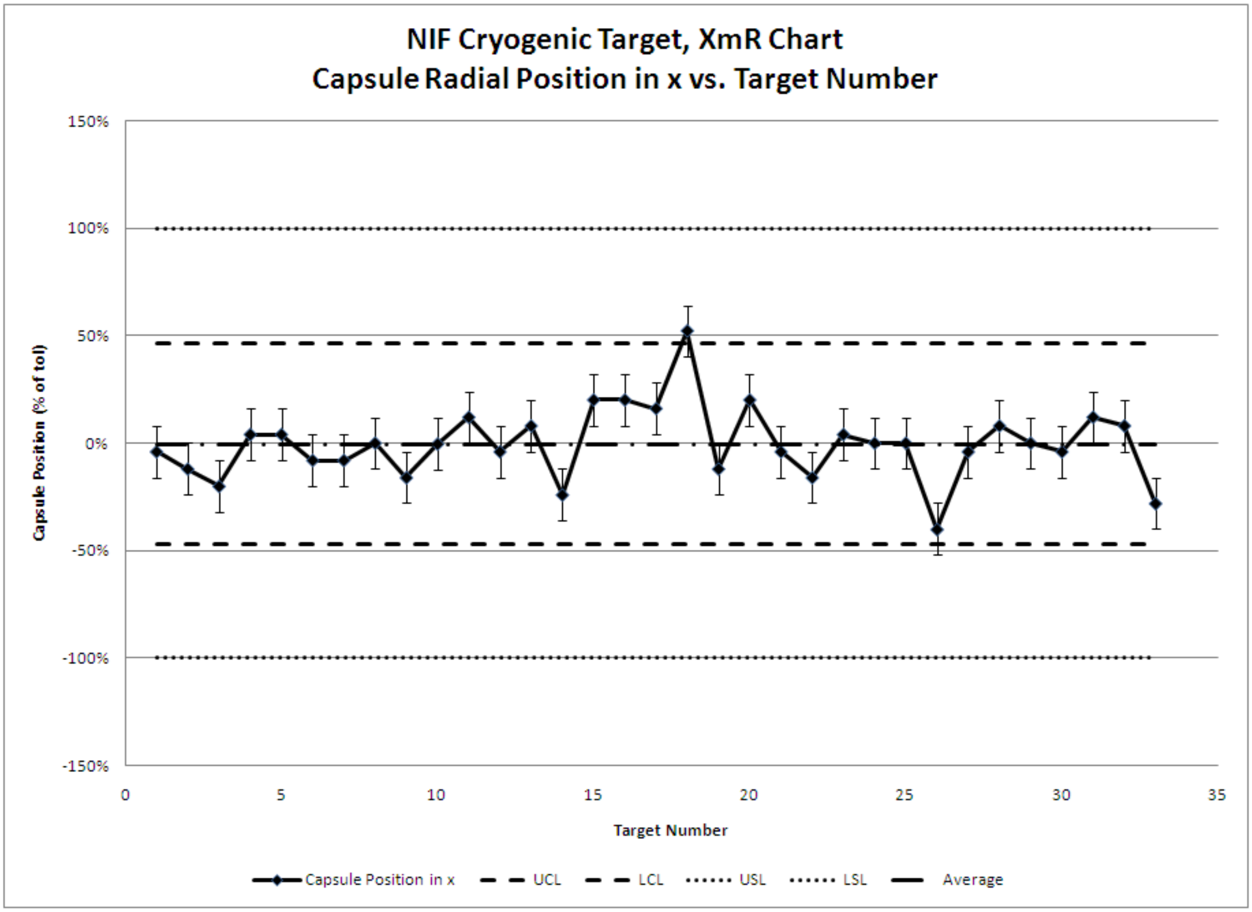

k. Figure 11: Target Rotation Relative to Base About X Axis Graph



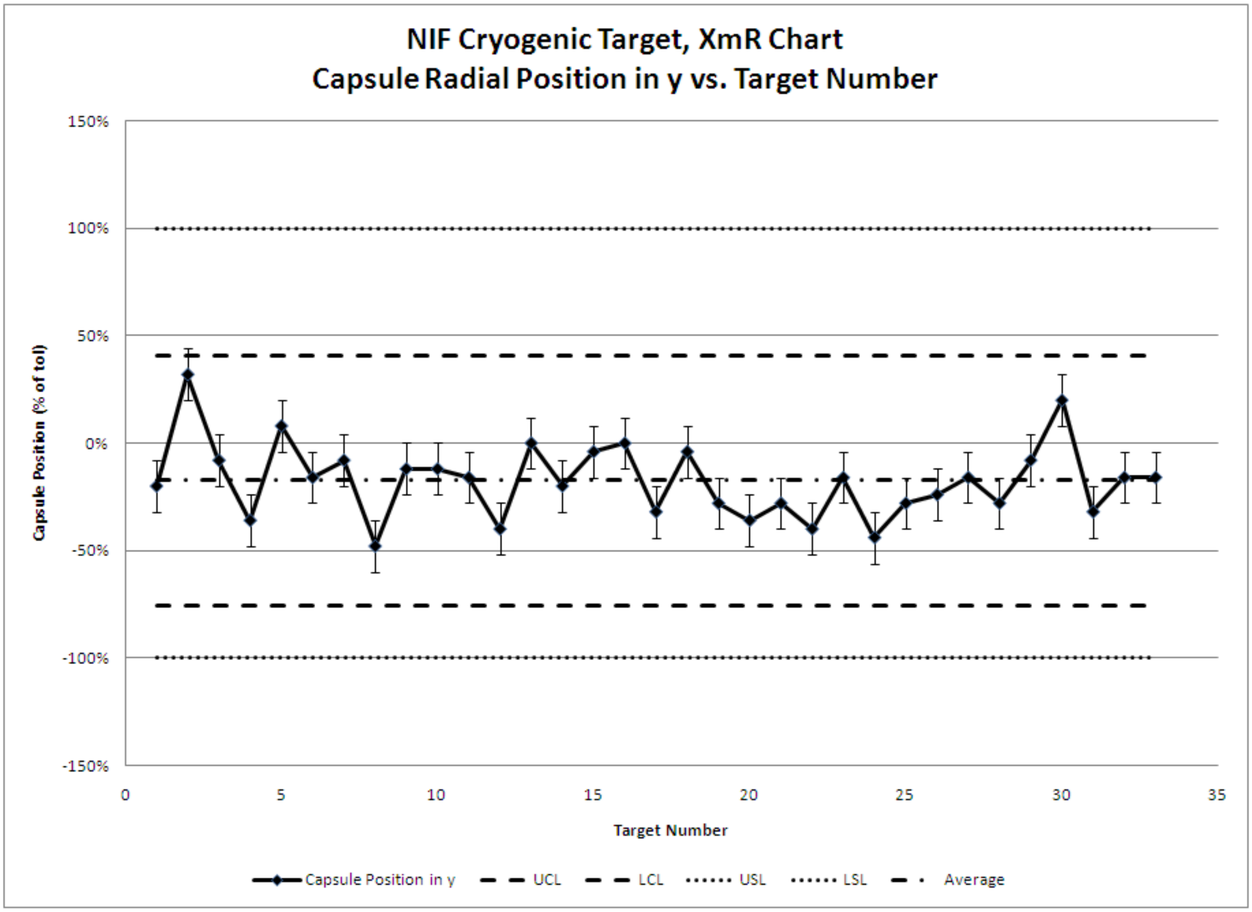

l. Figure 12: Target Rotation Relative to Base About Y Axis Graph



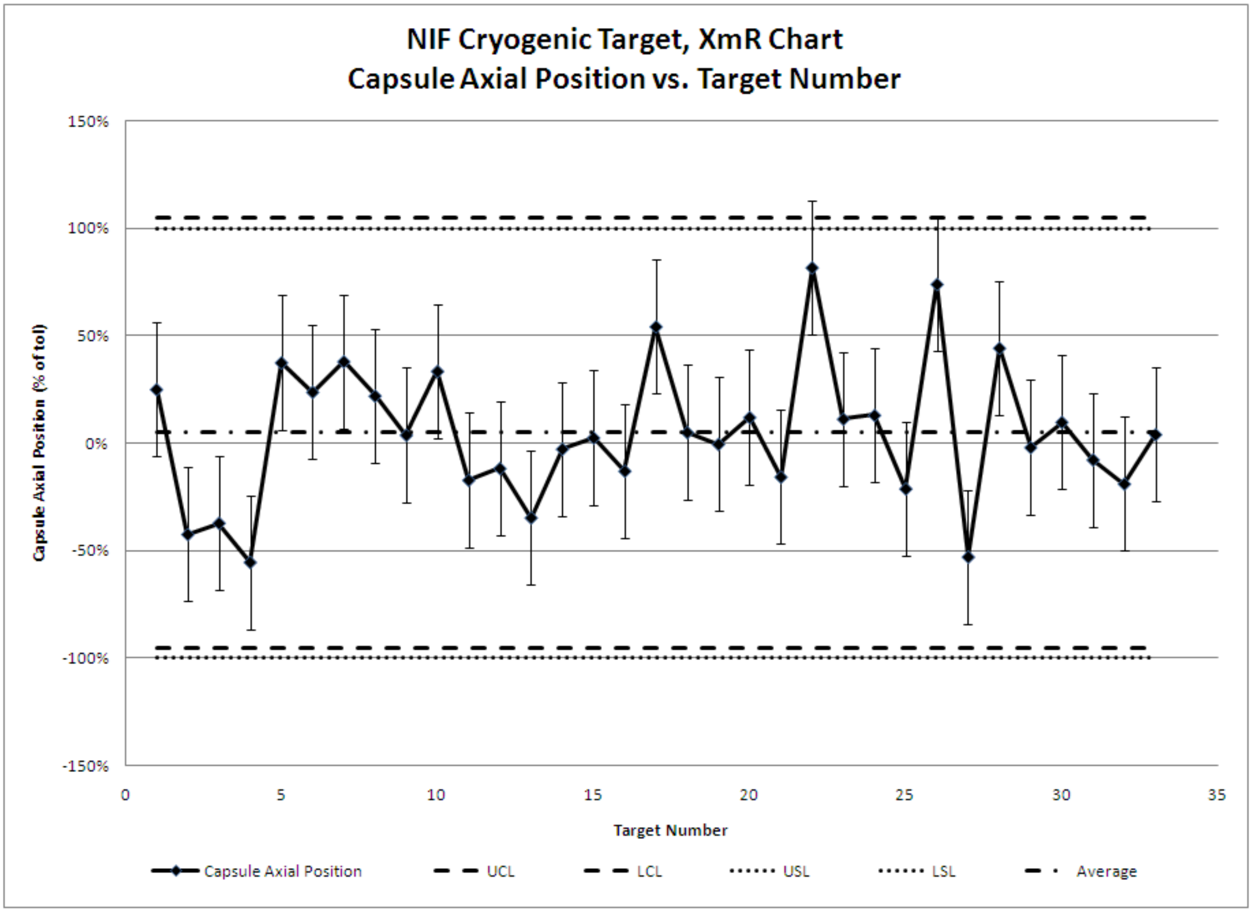

m. Figure 13: Capsule Radial Position in X Direction Graph




n. Figure 14: Capsule Radial Position in Y Direction Graph




o. Figure 15: Capsule Axial Position in Z Direction Graph


NIF Cryogenic Target, XmR Chart
Capsule Axial Position vs. Target Number
150%
100%
50%
0%
-50%
-100%
-150%
Capsule Axial Position (% of tol)
0
5
10
15
20
25
30
35
Target Number
Capsule Axial Position
UCL
LCL
USL
LSL
Average